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A THEORETICAL/EXPERIMENTAL PROGRAM TO DEVELOP ACTIVE OPTICAL POLLUTION SENSORS: PART II

FINAL TECHNICAL REPORT

By

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By

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SUMMARY

The author has had the good fortune to be able to contribute to ongoing programs in the Lidar Applications Section of the Environmental Science Branch of the Environmental and Space Sciences Division of the Space Directorate of Langley Research Center, to contribute to the delineation and planning of future programs, and to receive the full cooperation of all those at LaRC that he has worked with. The Table of Contents is the best summary of the many areas that he has been able to work on. These areas include the calibration and application of the LaRC 48-inch Lidar, efficient and certain detection of SO_2 and other gases in the calibration tank using the Raman Stack Monitor Lidar, the potential of Lidar remote sensing from the Space Shuttle, and the planning and mounting of two efforts to realize the promise of backscatter differential absorption Lidar.

It should be noted that this report does not include all of the sections listed in the Table of Contents. The omission of certain sections is explained later in the report (section IB).

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I. INTRODUCTION

The author's efforts during the term of this grant can be divided into those devoted to ongoing experiments in the Lidar Applications Section of the Environmental Sciences Branch, ESSD, SD, LaRC, and those devoted to planning future programs for the application of Lidar to environmental and atmospheric science.

A. Ongoing Programs

Many facets of the LaRC 48-inch Lidar system are just now being brought into operation. Complete atmospheric backscatter profiles can now be obtained from the cross-over height to the background limited height (i.e., 1 to 30 km) using the three photomultiplier switching option in the single analog channel of that system. This option allows a very large dynamic range in the return light signal with the otherwise limited range of present amplifiers and A-D converters, but proved quite difficult to align while looking at an actual atmospheric return. This alignment has been immeasurably aided by the installation and use of a pulsed light-emitting diode which imitates the return laser pulse. This light pulser has also been of great use in the evaluation and testing of the photon counting performance of both the Raman stack monitor lidar and the photon counting channel of the 48-inch system. The interpretation of these good quality atmospheric profiles is made difficult because of the intermixed molecular and aerosol contributions to the backscatter for a single wavelength lidar. One would like to find a means to separate these contributions in order to study the stratospheric aerosols and molecular profiles separately. The separation might be accomplished by locating a clean region of the atmosphere to which to peg an independently measured molecular profile (preferably taken simultaneously), by operating at a backscatter wavelength at which the stratospheric aerosol makes little or no contribution, or by operating in a Raman mode where the aerosol would not contribute to the return. A clean region does appear to exist near 30 km, but this region is at times obscured by ruby fluorescence background noise depending on the operation conditions.

The question of another Rayleigh backscatter wavelength also raises the issue of the utility of multi-wavelength measurements for learning something about the aerosols themselves. Since the 48-inch system has been provided with laser transmitters of several different wavelengths (although not all simultaneously), these two questions are addressed. The efficacy of multi-wavelength measurements for learning about the nature of the stratospheric aerosols is promising. In addition, depending on the nature of the aerosol, separation of the molecular scatter from the aerosol scatter is feasible for the doubled ruby frequency. The optimum way to achieve this separation and normalization for monitoring short term structure fluctuations is to operate with two simultaneous analog channels viewing ruby and doubled ruby frequencies. Next best is to alternate the single 48-inch system channel between these two wavelengths within a short period of time. The use of Raman scatter from the molecular atmosphere to accomplish the separation in the stratosphere is only useful over time periods of 6 hours at maximum lidar rates (i.e., 30 ppm), but this capability is quite sufficient for global climate questions. The potential of Raman nitrogen scatter from the stratosphere and below, and its relation to the separation problem are discussed in detail. The photon counting channel of the 48-inch system is being brought into operation to detect the Raman scatter. To this end, fast counting photomultiplier circuits and photomultipliers with the new high efficiency photocathodes and with the option of being gated for protection at close ranges are ready for installation. A number of other recommendations are made for improving and upgrading the LaRC 48-inch lidar. Preliminary Raman scatter measurements from heights up to 12 km have been taken with an RCA 8852.

The use of the photon counting system of the 48-inch lidar was explored for "ground truth" measurements of aerosols in the upper stratosphere and mesosphere once Nimbus G and an Atmospheric

Explorer satellites are launched. The lidar will need a fluorescence shutter (and probably a photomultiplier shutter) for these applications. Finally, the potential of the lidar for monitoring subvisible cirrus is discussed.

The author has studied in detail the efficient and certain detection of SO_2 and other gaseous pollutants in the calibration tank using the LaRC Raman Stack Monitor Lidar. This lidar system was meant to be compact and easy to operate so the spectral selection was to be done using interference filters. The dual problem of selection of the specific Raman wavelength from amongst other closely-spaced excited lines and of blocking strong returns at greater wavelength separations had previously resulted in interference filters near 7500 Å with poor transmissions. Quantitative measurements at the necessary 0.5 km ranges were thus made difficult with the desired modest optics. Wavelength selection and blocking was investigated in detail.

Before any field work could begin, it was necessary to clear up some problems in the photon counting system necessary to a remote Raman lidar of this size. The initial field trials were made viewing nitrogen in one channel and oxygen in the other channel of the optical train. Both the signal in each channel and the ratio of channel signals showed the expected behavior with range. The certainty of detection was proved by tuning the interference filters off the Raman scatter wavelength and by inserting filters corresponding to gases not present. Much effort went to making the tank apertures black enough so as not to break through the filter blocking at the ruby wavelength. The down-field beam dump serves as a good check on this source of systematic error. At the end of the reporting period, the attempts to obtain 3.7 for the ratio of nitrogen and oxygen concentrations by independently calibrating the channel sensitivities worked well to the 10 percent level. The full potential of the nitrogen channel for monitoring atmospheric extinction remains to be realized. High concentrations of CO_2 have been measured in the tank and have corresponded well to the 10 percent level with in situ CO_2 measurements in the tank. The very efficient C31034 photomultipliers have been installed in the low concentration pollutant monitor channel. However, the system still does not achieve its theoretical capability being about a factor of three less efficient. This discrepancy affects the operating time but not the measurement because of the use of the independent calibration. The projected performance for the 8-inch lidar placed 300 meters from a stack is a 10 percent measure of SO_2 concentration within 10 minutes if the factor of three can be recovered. Immediate plans call for the measurement of a low concentration of CO_2 in the tank, checks of filter blocking for SO_2 and CO_2 work in the presence of a typical stack aerosol, measurement of the transmittance of typical stack aerosols using the newly instituted dual channel mode of the photon counting system, and the measurement in the tank of gaseous pollutants such as SO_2 and HCl. A trip to an instrumented stack is also being planned. Finally, the potential of Raman lidar for monitoring water vapor concentrations, temperature, and absolute aerosol backscatter was addressed.

The author has contributed to the study concerning the potential of lidar for remote sensing from the space shuttle. He has been able to delineate the utility and practicality of lidar experiments in a document which ties together the many pieces of the studies now under way both in LAS and outside. The advantage of a lidar is its range resolution, its spatial resolution, and its specificity. Its disadvantages are its limited sampling and coverage capabilities due to its inefficient operation. The range and spatial resolutions of a cloud lidar can be used in a pilot study in collocation with a passive radiometer to signal when the radiometer is viewing cloud free grid elements. Long-term monitoring of both tropospheric and stratospheric aerosols and of water vapor in the mixed layer at night look possible as does surveying of upper atmospheric species.

B. Plans for Future Programs

The discussion of ongoing programs necessarily included short-term plans for the future. Longer range plans focused mainly on the new technique for studying the atmosphere called backscatter differential absorption. This technique allows either column content or range-resolved measurements of atmospheric constituents and pollutants based on the backscatter of two selected wavelengths. The promise for local and regional pollution monitoring is great compared to other techniques. LAS is proceeding to commission a tunable laser emitting in the near infrared where many pollutants have strong signatures in absorption. To make use of the resolution and data capacity of this pollution lidar, one will in all probability need a meteorological lidar which would supply the meteorological support data to the same time and spatial resolution. Measurements of humidity and temperature may be able to be made using the differential absorption technique. Measurements of extinction, mixed layer height, and wind velocity could be accomplished by extensions of lidar techniques now in use by LAS.

In preparing the capability to make use of the backscatter differential absorption technique, the author has recommended two experiments which can be accomplished at LaRC in the intermediate term. The first experiment is the measurement of NO_2 near large centers of automobile traffic using a tunable dye laser with two simultaneous outputs at the appropriate wavelengths in the visible. This experiment will be based on the capability demonstrated in the ALOPE program. The second experiment is the measurement of water vapor (and possibly temperature) using either a tuned ruby laser or a laser-pumped dye laser. It will be based on the capability demonstrated in the Raman Stack Monitor program although analysis has shown that its photon counting data system is best replaced with a multi-channel analog data system. One such analog system can be based on the temporary data system of the ALOPE program and suggestions were made for expanding its capacity to two simultaneous channels using the existing magnetic tape storage.

The author has aided in the definition of a much more sophisticated data system for use with the planned LAS lidar facility and with the pollution lidar. For example, a survey of techniques for extending the dynamic response of lidar was carried out with the result that the data system will incorporate gain-switched amplifiers in each signal line. Both of these differential absorption experiments should provide valuable experience not only with the necessary data systems but also the necessary optical techniques such as coarse spectral tuning, fine tuning, stability of tuning, etc.

The author has also looked at many other questions related to pollution and meteorological lidar and their potentials for atmospheric measurements. With respect to the question of whether or not there is sufficient backscatter from aerosols in the near infrared to proceed with the purchase of the pollution lidar, he concluded there was sufficient backscatter for limited range differential absorption experiments wherever maritime aerosol distributions are present. The competitiveness of Raman scatter measurements of aerosol extinction and water vapor distributions was also investigated. Examples of the joint use of pollution and meteorological lidars were found in studies of modification of the vertical temperature structure of the atmosphere by pollutants (e.g., NO_2 or aerosol layers).

Many other aspects of the work of the last year appear here as short sections or not at all for a variety of reasons. In some cases, separate papers have been published or will soon be published (e.g., Lidar Sensing from the Space Shuttle). In other cases, the sections are best reported as separate technical reports (e.g., the Raman Stack Monitor Lidar work). Much of the above work could not have been begun or carried out without the frequent help and advice of members of the Lidar Application Section and of other colleagues. To name a few; Burt Northam, Ellis Remsberg, Larry Brumfield, Lloyd Overbay, Bill Hunt, Jim Siviter, Carolyn Jones, and Gus Jarrett.

VI. REPORT OF TRIP TO SIXTH INTERNATIONAL LASER RADAR CONFERENCE SENDAI, JAPAN - SEPTEMBER 2-5, 1974

A. Abstracts of Talks Contributed

The Utility and Practicality of Lidar Remote Sensing Experiments From the Space Shuttle

Various atmosphere remote sensing experiments using LIDAR are now being considered for Space Shuttle. One of the more practical, from a signal point of view, is a cloud LIDAR which could supplement passive observations from satellites. It might, for example, map thin cirrus to aid in the reduction of infrared temperature (or constituent) soundings or measure cloud height directly to aid in cloud emissivity studies or inferences of atmospheric motions.

Signal/noise analyses of a single pulse measurement in several studies from Stanford Research Institute have defined achieveable LIDAR parameters, but LIDAR experiment feasibility depends on additional factors as pointed out so well for satellites by Evans, Wiegman, Viezee, and Ligda in 1966.

The dual requirements of coverage needed to supplement the satellite radiometer observations (or to make the other feasible LIDAR measurements useful) and of representative sampling in the process impose a stringent limitation on <u>all</u> Shuttle LIDAR remote sensing experiments. The many ramifications of these requirements during both day and night are explored here. In particular, they are shown to call for a repetition rate, and hence, electrical power for a conventional LIDAR which is, in many cases, far in excess of the Space Shuttle allotment to LIDAR experiments; even at night, and for state-of-the-art improvements in laser and receiver technology. If 8 km wide ribbon coverage is acceptable within the time constraints of one or more shuttle missions, and if 1 kw of electrical power is available, night LIDAR observations from the Space Shuttle appear practical and useful for clouds, aerosols, and water vapor. These observations would supplement other satellite observations in order to eliminate interferences, whether cloud, aerosol, or water vapor. Stratospheric and tropospheric aerosols can be studied in their own right. Water vapor observations would support the radar altimeter experiments such as on Skylab which itself bears close resemblance to the shuttle missions here considered.

Active Optical Techniques for Correction of the Water Vapor Contribution to the Index of Refraction of Air

Geophysical Measurements

Geophysical measurements requiring absolute determinations of distances between points in the atmosphere, determinations of distance from a satellite to the ocean surface, or absolute determinations of astrophysical source positions are susceptible to error due to the varying presence of water vapor in the atmosphere. The present sensitivity of optical geodimeters, satellite radar altimeters, laser ranging to earth satellites, and VLBI with respect to this error are reviewed. The potentials of the backscatter differential absorption laser technique (DIAL) and the Raman laser technique for monitoring column content of water vapor at the time of the geophysical measurements and along the same path are analyzed and then compared. Either technique can achieve measures of the column content of water vapor along a horizontal path in the absence of haze to support the geodimeter measurements, although DIAL yields the more direct result. Water vapor should be able to be determined to 1% and oxygen to 0.1% over a 16 km range within one-half hour in direct competition with other correction methods. A space shuttle or satellite DIAL lidar collocated with a nadir-looking radar altimeter should be able to make the water vapor correction to 10%.

Supplementation of VLBI measurements is much more difficult for optical techniques because of its all-weather nature. Raman lidar here gives a more direct result and should allow a 10% measure of water vapor along the vertical and to zenith angles of 60° within one-half hour.

Photon Counting vs. Analog Detection Systems in Laser Radar Studies of the Atmosphere

Raman scatter monitors of low concentration pollutants naturally make use of photon counting in the visible whereas Rayleigh/Mie scatter monitors of nitrogen/aerosols in the lower atmosphere naturally make use of analog current detection. The details of a 200 mHz, dual channel, sixteen bin, variable bin width, 22 accumulation bit per bin, photon counting system in use at NASA-Langley Research Center is exposited with respect to its use for SO_2, H_2O, and other gas monitoring. The other channel is a single bin at present. The application of a full dual channel photon counting system to backscatter differential absorption experiments is discussed with the result of a unique choice for the mode of operation of the laser transmitter. The details of a dual channel analog LIDAR is then exposited for the same differential absorption experiment. The advantages of both systems are discussed in their respective regimes and the region of overlap is critically appraised. Verification of the analysis is presented based on laboratory simulation of the laser return pulse using a pulsed light emitting diode. The use of photon counting techniques to characterize such a light pulse and tips to achieve photon counting at high rates are also presented.

VII. THE CAPABILITIES AND POTENTIAL OF LASER TECHNIQUES FOR MEASUREMENTS IN THE UPPER ATMOSPHERE

Invited Paper Abstract: Conference on the Upper Atmosphere October 1974

Three classes of experiments using laser techniques for measurements in the atmosphere above the stratosphere have been carried out from the ground. These are monitoring of the molecular density up to 100 km, monitoring of distributions of several of the trace alkali atoms in the vicinity of 90 km, and observations of noctilucent clouds and other aerosols near 80 km. The accuracy and utility of these observations from the ground are reviewed with respect to the several time scales of interest ranging from seasonal to internal gravity wave periods. Projections are then made as to the future of ground-based measurements and the potential of similar measurements from either an aircraft or the space shuttle. The further use of laser backscatter techniques such as Raman scatter, resonance scatter, and differential absorption is explored within the context of the presence of the space shuttle in the upper atmosphere. In particular, local monitoring of atomic oxygen concentrations by resonance scatter appears attainable if uv laser technology continues at its present course.

Trip Report. The Conference on the Upper Atmosphere, Atlanta, Georgia, October 1974

S.K. Poultney attended two days of the five-day conference. He presented an invited 20 minute paper on the Capabilities and Potential of Laser Techniques in the Upper Atmosphere. The sessions attended by S.K. Poultney were (1) Techniques, and (2) Techniques Workshop with a brief period spent in the Theory Workshop during its conclusive phase. Each workshop tried to summarize the present state of experiment and theory for use in the next day's synthesis session. These synthesis sessions will be summarized in a paper to appear in the Bulletin of the American Meteorological Society written by Dr. Roper of Georgia Institute of Technology.

There was general interest in the lidar technique after my review and at the workshop the next day. Interest ranged from precisions of density measurements possible to number of units in operation to the mobility of those units. A number of people were interested in lidar measurements of the stratosphere; both aerosols and temperature structure. I gathered that lidar techniques are competitive with other techniques in some cases and unique in others. Monitoring of diurnal to seasonal changes of molecular density are competitive with rocket soundings between 40 and 80 km and with meteor radars between 80 and 100 km. Measurements of winds between 80 and 100 km based on aerosol or sodium motion correlations appears competitive with meteor radar techniques. Lidar can uniquely monitor Na, K, and perhaps O concentrations. It may uniquely monitor temperature between 80 and 100 km if the Na doppler linewidth measurements are further developed. It can uniquely determine the layer structure of Na and noctilucent clouds over small horizontal area samples. It may also be a good monitor of suspected aerosol accumulations near the stratopause. In raising the issue of these lidar applications, it is well to recall that the Langley 48-inch lidar would function well as an upper atmosphere lidar given a 1 pps, several joule ruby or doubled YAG laser or a 1 pps, several hundred millijoule dye laser.

Specific inquiries are listed below along with the name of the questioner.

Sechrist - University of Illinois: Interested in Na behavior at 90 km w/r to electron density.

Reed - GSFC: O concentrations w/r airglows.

Robbins - JSC: Works with Hudson. AMP program summer study report from Woods Hole is available. Requested information from LaRC on lidar experiments from the shuttle.

MSFC Contact: Thinks they are in charge of shuttle laser experiments. Should contact Lindquist.

Gille - NCAR: Interested in Na doppler widths at 90 km for temperature measurement at 90 km above height reached by his Nimbus F radiometer.

C. Johnson - NRL: Interested in natural Na or aerosol or injected Na, K, or aerosol at other heights tracked by lidar as tracers for winds.

Snider - BRL: Interested in measurement of atmospheric density and temperature from 40 to 80 km.

Kent - Jamaica: Main interest is seasonal and tidal variations in atmospheric density. Asked about possibility of Raman detection of water and ozone in stratosphere similar to N_2 monitoring. He has done latter and we at LaRC plan to try it. The monitoring of H_2O and O_3 by Raman appears dim since N_2 monitoring (to 1%) takes all night and the two minor constituents are down by a factor of 10^6. Even a 10% measure takes too long.

Minzner - AFCRL: Derived temperature-height profiles are best gotten from density measurements rather than pressure. Over a wide range of conditions 1% errors in density lead to only 1% error in temperature.

Snider - BRL: Interested in electron densities near nuclear explosions. Concentrations not stated, but I have estimated that 10^5 per cc at 200 km does not give enough Thomson scatter to be seen above Rayleigh from atmosphere.

Brief Summary of Theorist Workshop

Need zonal distribution of stations looking at tides up to 100 km.

Eighty to one hundred region important in models because it is the upper boundary condition to circulation models. Diffusion is important above 105 km, not eddy motions, etc.

Day to day tidal and other density variations are important between 30 to 60 km w/r to coupling of stratosphere and mesosphere.

Nimbus F ground needed in 1975 to calibrate its observations up to 70 km.

Technique badly needed to measure vertical winds directly in all levels of the atmosphere; especially the tropics.

Question of solar cycle variations of stratosphere temperature.

VIII. LIST OF PAPERS PRESENTED AND TO BE PRESENTED

"The Coverage and Sampling Limitations of Lidar Remote Sensing Experiments From the Space Shuttle," EOS Trans. 55, p. 274 (April 1974).

"Active Optical Techniques for Correction of the Water Vapor Contribution to the Index Refraction of Air in Geophysical Measurements," Bull. Am. Phys. Soc. Ser. II, 19, p. 604 (April 1974).

"Photon Counting vs. Analog Detection Systems in Laser Radar Studies of the Atmosphere," Sixth International Laser Radar Conf., Sendai, Japan (September 1974).

"The Utility and Practicality of Lidar Remote Sensing Experiments from the Space Shuttle," Sixth International Laser Radar Conf., Sendai, Japan (September 1974).

"Active Optical Techniques for the Correction of the Water Vapor Contribution to the Index of Refraction of Air in Geophysical Measurements," Sixth International Laser Radar Conf., Sendai, Japan (September 1974).

"The Capabilities and Potential of Laser Techniques for Measurements in the Upper Atmosphere," Invited Review Paper, Conference on the Upper Atmosphere, Atlanta, Georgia (October 1974).

"Lidar Sensing of Water Vapor in the Atmosphere," Invited Seminar, University of Missouri (October 1974).

"Laser Radar Studies of the Upper Atmosphere," Invited Seminar, University of Illinois (October 1974).

"Stratospheric Aerosol and Thin Cirrus Monitoring from Both the Ground and the Space Shuttle Using Lidar," in preparation for submission (Fall 1974). With E. Remsberg.

"Testing the Linearity of Response of Gated Photomultipliers in Wide Dynamic Range Laser Radar Systems," Nuclear Science Symposium, (December 1974). With W. Hunt. Also IEEE Trans. Nucl. Sci., NS-22, 1111 (June 1975).